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ORIGINAL ARTICLE

Study on a stepped eco-filter for treating greywater from single farm household

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Abstract A stepped eco-filter based greywater treating facility was built on-site in a typical farm house of China. This study was aimed to investigate the hydraulic loading rate (HLR) for the optimal removal efficiency and to analyze the processing performance throughout an entire year. The results showed that, the average value of TP from the influent was much lower while the linear alkylbenzene sulfonate was a little higher compared with other related studies. The removal rates of the indexes were all showed a distinct decline and dropped to a low level while the HLR was raised from 0.2 $m^3/(m^2$ day) to 0.4 $m^3/(m^2$ day). Therefore, the optimal HLR of the process ought to be in the range of 0.2–0.4 $m^3/(m^2$ day). The average system removal rates in summer were all higher than that in winter, but the facility still performed well in winter. Clogging has never occurred in the facility during the operation over an entire year. Together with the good performance, advantaged of lower cost and easier maintenance, this process has shown good applicability for greywater treatment in rural area.

Keywords Greywater · Eco-filter · Farm household · Hydraulic loading rate · Linear alkylbenzene sulfonate

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Introduction

Pollutions resulting from the domestic liquid waste have largely increased in current China due to the intensified use of chemical products driven by the rapid economic development. The large amount of untreated domestic sewage caused serious degradation of the natural water quality and led to serious environmental damage (Wang et al. 2011); thus, it is urgent to develop suitable technologies for treating domestic wastewater in China's rural regions. The rural domestic sewages can be segregated into greywater (GW) and black-water (BW), the GW is generated from washing basin, bathroom, kitchen, laundry and black-water is mainly from toilet and farm life stock (Halalsheh et al. 2008). Our previous field survey showed that BW generated from the most peasant households has been already collected by septic tanks and reused for fertilization in the region, but the GW was normally discharged directly into the drainage ditch and then flowed into the streams. Therefore, this study is aimed to investigate the process for the treatment of rural GW and to build a practical system on-site.

In comparison with the traditional centralized urban wastewater treatment, the decentralized process is likely to be low in both operating and initial cost because no large sewage pipe system is needed. Currently, the decentralized techniques adopted for GW treatment can be categorized into three groups: physical, chemical, and biological systems. Physical methods include sand and membrane filtration, and the chemical methods include coagulation and ion exchange (Marc et al. 2007; Huelgas and Funamizu 2009). The biological system mainly include membrane bioreactors (MBR), anaerobic sludge blanket (UASB), constructed wetland (CW), and vermifiltration (VF) (Li et al. 2009; Wang et al. 2010). When treating the GW from households, more and more studies focus on the bio-ecological technology due to the potentially low cost, high efficiency and easy maintenance desired by potential users. A recycled vertical flow constructed wetland showed an overall removal rate of 81% for COD and 70% for TN and TP, and the treated GW sufficiently to meet current standards for unlimited irrigation except for the complete removal of Fecal coliforms (Gross et al. 2007). An comparative study showed that shallow beds led to higher BOD_5 and COD removals, wherever the presence of plants in the vertical flow constructed wetland (VFCW) caused higher removal rate of the linear alkylbenzene sulfonate (LAS) (Kadewa et al. 2010). A low cost and simple slanted soil system has been reported to perform high removal rate in both PCOD (94–97%) and BDOC (88–89%), whilst the LAS removal rates were more than 90% and final concentrations (2.3–3.3 mg/L) were sufficiently lower than the level for irrigation use (Ushijima et al. 2013). Adugna et al. (2014) reported that the vermifilter was better than the filter without earthworms in removing BOD_5, COD, TSS and coliforms, and higher removal rates were achieved with the HLR of 0.064 $m^3/(m^2$ day) compare to 0.19 $m^3/(m^2$ day) in all parameters.

In recent years, more and more research focus on the characteristics of domestic GW and the GW treatment process (Ghaitidak and Yadav 2013; Jabornig 2014; Edwin et al. 2014). However, many of the stimulated tests were carried out in the lab for a relatively short period of time. The correlative changes between the pollutants removal efficiency and the process parameters, such as the hydraulic loading rate (HLR) have been rarely interpreted. In addition, our field survey showed that the trenching process such as the conventional CW was out of the question because of a thin soil cover (15–25 cm) on the ground around the farm house. In light of what have been mentioned above, a set of improved stepped eco-filter (EF) process based on the CW and the VF was designed above the ground to treat the GW from a farm household in mountainous rural regions. The aim of this study was to investigate the operating parameters for the maximum removal rate of an on-site EF process constructed according to the local conditions while treating the GW from a single farm house, as well as its general performance during the operating period of an entire year.

Materials and methods

Pilot plant setup

The pilot facility was built in a typical farm house located in the Three Gorges Reservoir region of China, which were composed of influent collecting pipes, one settling tank, and two ecological tanks. These units were connected sequentially and positioned from high to low elevation to allow for gravity driven fluid flow. This way, the facility could operate without energy consumption (Fig. 1a). All the tanks were handled by PVC frame, which measures 80 cm long, 60 cm wide and 65 cm high, respectively. The water distributors were made of a row of PVC pipes that each was drilled with six small holes (2 mm diameter). These distributors were placed 20–30 cm above the surface soil of the tanks. Cock taps were inserted near the bottom of the tanks for the sampling of the effluent.

From the bottom to the top, the ecological tanks were designed as catchments layer (0–10 cm), board supporting layer (10–12 cm), slag layer (12–22 cm), gravel layer (22–32 cm), soil layer (32–60 cm) and vegetation layer. The slag and gravel were solid waste collected in the village, the physical characteristics of the slag and gravel was shown in the Table 1. The soils were collected from the mountains near the farm house, which was evenly mixed with sands by volume ratio of 3:1. Earthworms were collected from the vegetable garden nearby and were put into the soil layer with the density of 40 worms per square meter of soil. In the vegetation layer, ornamental and evergreen plants were planted using *Ophiopogon japonicus* and *Rhododendron simsii Planch*; a good long-term stability of landscape of the EF was formed as these plants live a normal life all year around (Fig. 1b).

Experimental design

In regular sequence, this experiment was divided into three stages including the set-up phase, the HLR optimization test and the continuous operation test. The set-up phase was designed for the acclimatization of the microorganism, earthworms and plants. Influent GW was collected by PVC pipes from the typical single household. Operating period of the process was set from 9:00 to 15:00 everyday, and this was automatically controlled by a relay and a peristaltic pump; so the wet-to-dry time ratio was maintained at 1:3. The duration of the set-up phase was 60 days, and the influent flow rate was designed as slow as 65 mL/min, or a HLR of 0.05 $m^3/(m^2$ day). The period of the HLR optimization test was planned as 100 days, the HLR was designed four stages as 0.05 $m^3/(m^2$ day) (stage 1), 0.1 $m^3/(m^2$ day) (stage 2), 0.2 $m^3/(m^2$ day) (stage 3), 0.4 $m^3/(m^2$ day) (stage 4) with the operating time of 20, 20, 20, 30 days, respectively. To investigate the long-term performance of the process under the HLR of 0.2 $m^3/(m^2$ day), the continuous operation test was operated continuously over an entire year. The adjustable valve was used to maintain the HLR condition instead of using the peristaltic pump; thus, the GW was flowing by gravity and the process operating without energy consumption in this period.

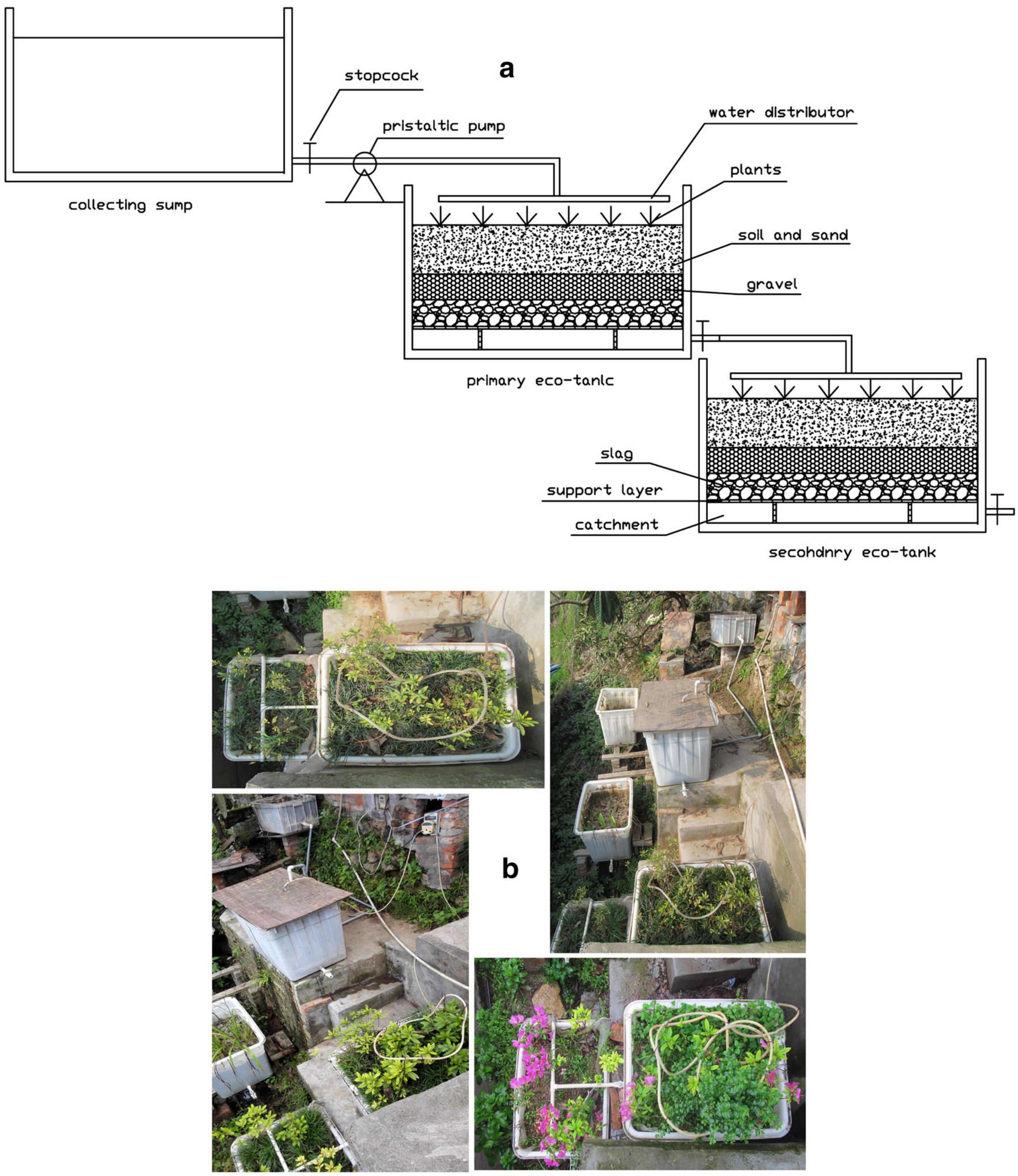

Fig. 1 **a** Schematic diagram of EF; **b** photographs of the EF in different seasons

Table 1 Characteristics of the block fillings in the EF

Fillings	Particle size (cm)	Apparent density (g/cm^3)	Actual density (g/cm^3)	Particle porosity (%)	Packing density (g/cm^3)	Packing porosity (%)
Gravel	1–2	2.63	2.66	1.13	1.40	38.7
Slag	2–4	2.10	2.71	22.5	0.692	74.5

Sampling and analytical methods

Influent and effluent of the system were sampled and monitored continuously during the experiment period. The COD, NH_4^+-N, TP, and the LAS were measured according to the Standard Methods for the examination of water and wastewater (APHA 1998). The removal efficiency was calculated as the percent removal for each parameter: $R = (1 - C_e/C_i) \times 100\%$, where the C_e and C_i are the influent and effluent concentrations in mg/L, respectively. The pH and temperature were determined in situ by the portable pH meter (OHAUS STARTER 300, USA), and the moisture content in the soil was measured on-site by portable soil moisture tester (TRIME-P, Germany).

Statistical analysis

Analysis of the experiments data was performed by the software of SPSS 16.0 and Surfer 8.0, and the p value less than 0.05 ($p < 0.05$) was interpreted to declare the differences of significant level. The one-way analysis of variance (ANOVA) and the least significant difference (LSD) was performed to analyze the differences between average values of the effluent for each physicochemical parameter.

Results and discussion

Effect of the HLR on the removal rates of the process

The set-up phase lasted about 60 days, which was mainly aimed to observe the adaptation of the earthworms and plants in the ecological tank. The effect of the GW distribution was tested in the wet and dry period separately, 20 sampling points for moisture measurement were set in the horizontal plane at the depth of 15 cm under the soil surface in each tank. The test results showed that the moisture

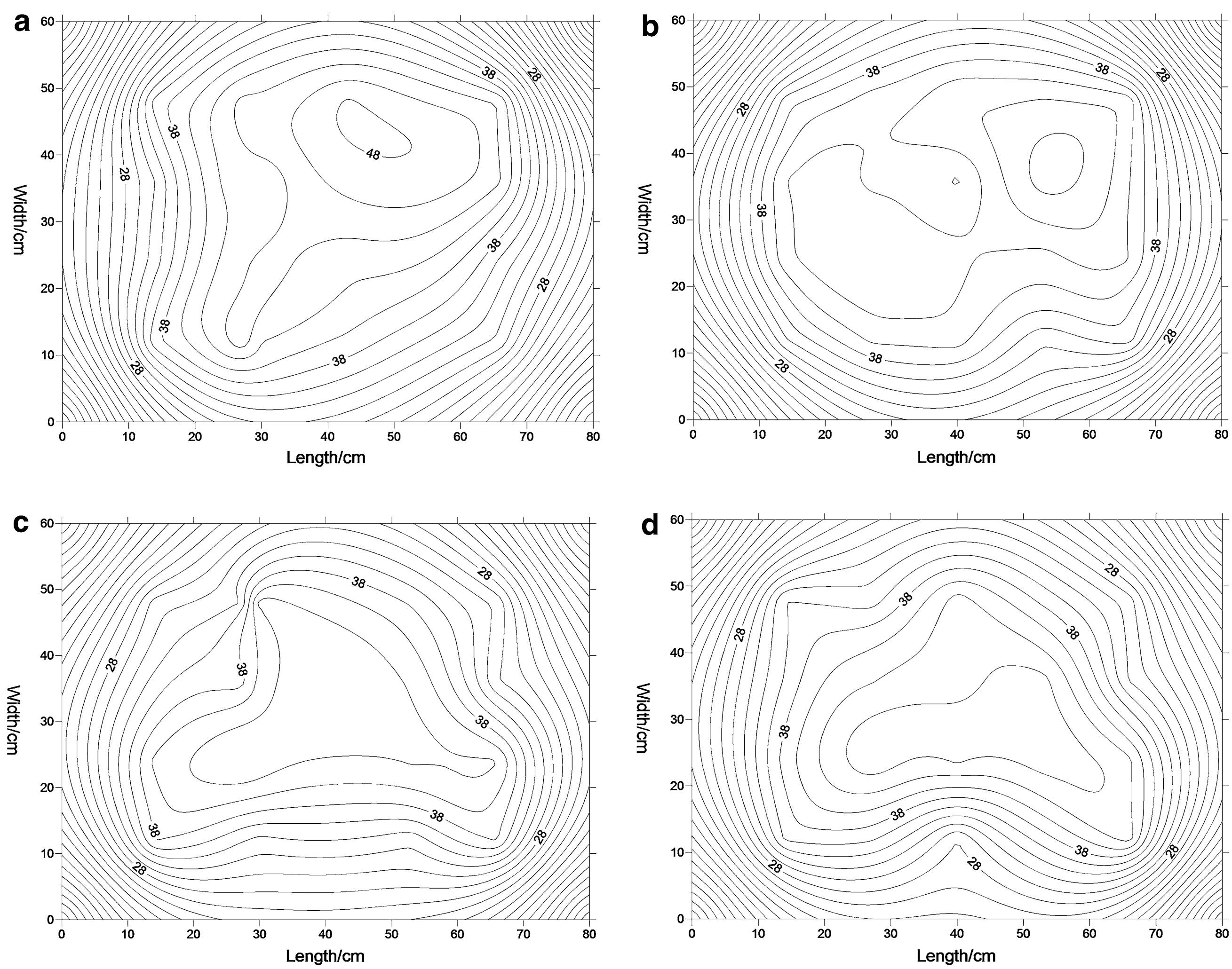

Fig. 2 Contour of the soil moisture content in the two tanks: **a** the first tank in the wet period; **b** the first tank in the dry period; **c** the second tank in the wet period; **d** the second tank in the dry period. The results are represented in percentage (%)

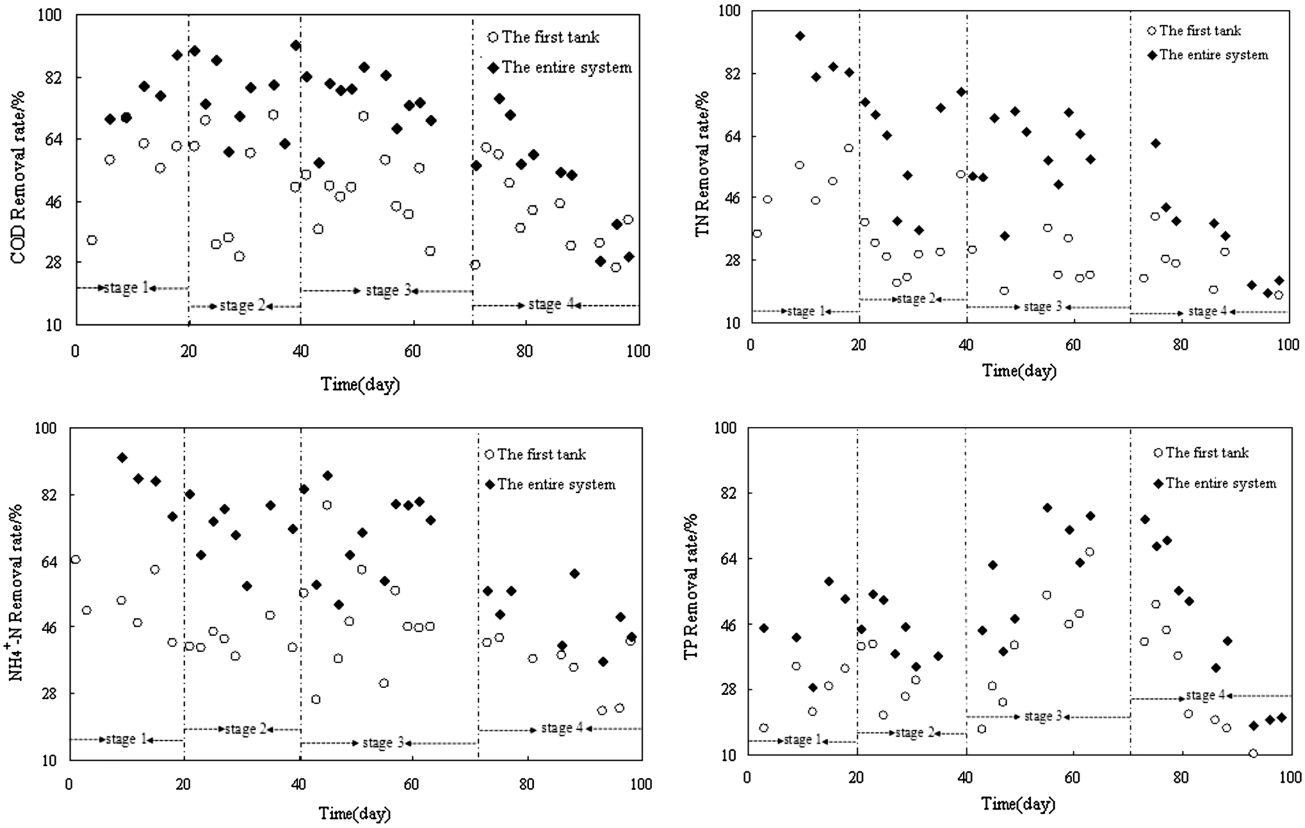

Fig. 3 Effect of HLR on the removal efficiency of the process

was evenly distributed in the soil layer of the two ecology tanks (Fig. 2).

In the 30th day of this period, the plants thrived well and earthworms could be found alive after scooping up handfuls of soil. Then, the COD, TN, NH_4^+-N, TP of the influent and effluent of the first ecological tank was monitored for a month. The average removal efficiency of COD, TN, NH_4^+-N, TP during the set-up phase was 63, 64, 77 and 59%, respectively. All the indexes of the influent gradually decreased, but the removal rates of COD, TN, NH_4^+-N showed comparatively stable except for TP, this may attributed to the rather low content of TP in the influent. Moreover, the frequent rains in that period caused the decline of all the indexes of the influent.

Thus, covers and GW collecting pipes were designed to eliminate the effect of the rainfall after the start-up experiment. The removal rate changes of COD, NH_4^+-N, TP, turbidity during the HLR optimization test are presented in Fig. 3, and the HLR was designed four stages from stage 1 to stage 4 with the value was 0.05 $m^3/(m^2$ day), 0.1 $m^3/(m^2$ day), 0.2 $m^3/(m^2$ day), and 0.4 $m^3/(m^2$ day), respectively. From the change regulations of the removal rates in Fig. 3, it can be concluded that the optimal HLR of the process will located in the range of 0.2–0.4 $m^3/(m^2$ day). Compare to the similar processes, the optimal HLR of this process was a little higher as the HLR reported in the related studies were 0.06–0.25 $m^3/(m^2$ day) (Luederitz et al. 2001; Kantawanichkul et al. 2013). It may attribute to the reason that the fillings mode and the operation condition of this process were different from the VFCW, although it was more similar to the VFCW compared to the other ecological process.

The removal rates of COD, TN, NH_4^+-N, and TP changed differently with the increasing of HLR from 0.05 to 0.4 $m^3/(m^2$ day), as was shown in the Fig. 3. The removal rate of COD, TN, NH_4^+-N, and TP were all gradually declining with the increasing of HLR, while the further decline was observed under the HLR of 0.4 $m^3/(m^2$ day). The hydraulic retention time (HRT) was shorter when the HLR was up-regulated; therefore, the interception and the absorption functions of the EF were degraded at the same time. With the increasing of the HLR, the removal rates of the most indexes represented the trends of reduction; this is also consistent with the most of the previous works.

Unlike the other related works, the removal rate of TP increased as the HLR elevated from 0.1 to 0.2 $m^3/(m^2$ day) before decreasing during the HLR increased from 0.2 to 0.4 $m^3/(m^2$ day). The removal of the TP in the EF system mainly due to the absorption and precipitation of phosphorus on the packing, and the maximum adsorptive capacity could be enhanced with the increment of the TP content in a certain range (Cheol et al. 2005). In this study, the concentration of TP in the influent was much lower compared to other reports, which is the reason for the low removal rate. In similar, it explains why the TP removal rate was increasing as the HLR was up-regulated from 0.1 to 0.2 $m^3/(m^2$ day) (Fig. 3).

Treatment performance of the process in the continuous operation test

Based on the conclusions of the HLR optimization tests, the process was operating continuously under the HLR of 0.2 $m^3/(m^2$ day) over one entire year. The COD, NH_4^+-N, TP, turbidity and LAS of the influent and the effluent Water from the influent, effluent (including the first tank and the entire system) were sampled and monitored 3–4 times every month during the year. The average values and the removal rates was calculated and listed in Table 2.

Compared to the general characteristics of GW data collected by previous studies (Donner et al. 2010; Ghaitidak and Yadav 2013), the means of COD, TP, turbidity and pH in this study were within the same rang. However, the data from this examine were all in a comparatively lower range. This is because the GW was mainly from the bathroom and the wash basin in this experiment, a much lower percentage of sources from laundry and kitchen considerably reduces the organic load and total solid content of the GW. Furthermore, the characteristics of COD, TP, turbidity in GW from this farmer household were more consistent with the water quality from bathroom (Ghaitidak and Yadav 2013; Assayed et al. 2015). These results support the conclusion that the characteristics of greywater are mainly determined by the source, lifestyle, and daily activities of the household (Eriksson et al. 2009). Variations of the LAS in GW had rarely been elucidated in the related research, and the data of which from our study were in the range but in a comparably high level than that from the other investigations. It may attribute to the fact that the GW in this experiment are mainly composed of washing dishes and laundry water from farmer household, which contains a large amounts of LAS because of the excessively use of detergent and soap by the family members.

In this study, concentration of the TN, NH_4^+-N and TP in the effluent satisfied the need of "Urban Sewage Treatment Plant Pollutant Discharge Standard" (GB18918-2002) primary standard Class A, and the content of the COD met the secondary standard. The GW output of a household within a day varies considerably in different seasons through out a year. On the whole, the average amount of the greywater generated from the household was in the range of 0.1–0.4 m^3/day in the rural area. Initially, we did not intend to treat all the greywater discharged from the peasant household in this experiment. Our purpose is to investigate a range value of the optimal HLR of this process by treating part of the discharged greywater. The results showed that, the optimal HLR of the process was ought to be in the range of 0.2–0.4 $m^3/(m^2$ day). Based on this result, it can be concluded that when we set out to treat all the greywater from the peasant household in future practical application, we only need to increase the surface area of our EF tank to some value of 1–2 m^2 based on the data of this experiment.

In addition, the removal efficiency of the COD, TN, NH_4^+-N, TP, turbidity, LAS averaged to be 67, 55, 64, 43, 68, 71%, respectively (Table 2). The removal rates of COD and TP in this examine was obviously lower than the most related facility (Wang et al. 2011; Zhao et al. 2012), it is due to the fact that only two EF tanks (the first tank and the second tank) were concatenated in this study but three tanks were designed in their experiment, added with the big fluctuations of the influent character during the entire year. As can be deduced from our data, the removal efficiency of COD and LAS could be enhanced to satisfaction if the third EF tanks or recycling measures are in further connected to the process. The removal rate of LAS was averaged as 71%, which mainly attribute to the living plants and the depth of the packing (Huang et al. 2004; Kadewa et al. 2010). Despite the removal rate of LAS was not so good by the this EF process, the content of LAS in the influent was

Table 2 The concentration and the removal efficiency of the process in the continuous test during an entire year

Items	Sample size (n)	Influent[a]	Effluent[a]		Removal rate (%)[a]	
			The first tank	The entire system	The first tank (%)	The entire system (%)
COD (mg/L)	58	302 ± 110	151 ± 82.7	98.5 ± 49.4	50.6 ± 12.7	67.2 ± 15.3
TN (mg/L)	48	12.2 ± 5.59	7.36 ± 2.35	5.67 ± 2.37	35.1 ± 17.5	54.5 ± 12.8
NH_4^+-N (mg/L)	58	7.04 ± 2.25	3.59 ± 2.51	2.59 ± 2.00	50.4 ± 21.1	63.5 ± 16.6
TP (mg/L)	58	0.922 ± 0.319	0.551 ± 0.139	0.480 ± 0.115	35.2 ± 16.2	43.3 ± 12.8
Turbidity (NTU)	53	106 ± 49.1	62.9 ± 32.9	34.5 ± 20.3	40.5 ± 19.0	67.6 ± 14.4
LAS (mg/L)	32	55.3 ± 15.7	31.8 ± 6.79	15.82 ± 4.90	42.6 ± 3.52	71.4 ± 5.24
pH	58	7.58 ± 0.261	7.79 ± 0.204	7.86 ± 0.198	–	–

[a] Mean concentration ± standard deviation of the physicochemical parameters

near to the discharge standard, and predictably the content of LAS in the influent will lower than the discharge standard if a third similar tank was added and connected to this process.

Technologies including physical, chemical, and biological systems were already applied for GW treatment. Up to date, the technologies of membrane filtration, such as membrane bioreactor (MBR) or direct UF/MF filtration, are more frequently used for the single households GW treatment by the water-treatment companies, however, the investment of MBR for single household is still too high when the payback time is almost 15 years (Jabornig and Favero 2013; Jabornig 2014). Householders' poll showed that about 23% respondents were reluctant to pay any money on the sewage treatment facility, which means that the cost of the facility must be extremely low so that the rural villages could accept it (Wu et al. 2011). In this study, the sum construction cost including the experimental expense of the process is very low as 160 US dollars (Table 3). Since a large proportion of the cost is from the frame structure and the installation, a big reduction of the sum cost can be acquired by directing the farmer to build and install the frame structure using cheap raw material such as concrete.

Clogging is the biggest problem to the most bio-ecological processes such as the Constructed Wetland and the Filtration. However, clogging was not experienced in this study, probably because the trapped solids in the soil were preyed by the earthworms or degraded by the microorganisms promptly. In addition, the packing porosity in the gravel layer and the slag layer are both in a comparably high level (Table 1), which may have reduced the chance of clogging happening. The EF is easy maintaining because of the following reasons: (1) it was designed according to the terrain conditions of hilly areas, which run by gravity and do not need additional equipment such as pumps; (2) the process has showed stable treatment effect during an entire year and no clogging was observed during the period, the only required maintenance was pruning the plants and pulling the weeds in the tanks. From what have been discussed above, it could be concluded that with the advantage of lower cost and easier maintenance, the EF technology with its improvements for GW treatment has high applicability in the rural areas of developing country.

Table 3 Construction and experimental cost of the household ecofilter

Items	Cost (US dollars)
Precast frame structure	30
Gravel, slag and soil	0–5
Installation	100
Pipes and joints	20
Plants	0–5
Excavation	0
Sum	160

Impacts of the environment temperature on the process

The effect of the air temperature on the performance of the EF was examined based on the comparison of the data from the summer and winter in a year, with the temperature 21–30 °C in summer and 5–12 °C in winter. In the summer, the system removal rate of COD, TN, TP, LAS was 77, 65, 45, 76% and the corresponding value in the winter was 60, 48, 41, 68%, respectively. All the removal rates from summer were observed higher than those from winter, and this was in agreement with the previous study (Zhao et al. 2012). In contrast, the removal rate of TP in winter was in close proximity to that in summer, and the significant different ($p < 0.05$) of removal rate between the summer and winter was only detected in COD (Fig. 4). Probably, the very low concentration of TP in the influent has limited the increase of the removal rate to phosphorous in summer. Due to a similar reason, the significant difference of removal rates between summer and winter could only be detected in the index of COD, for the COD content in the influent was moderate according to the GW quality reported previously.

While treating the GW, the mechanisms of the EF included the filtering absorption in the layer of soil and packing, and the bio-chemical retention of the plant root and microorganism. Moreover, the existing of the earthworm was proved effectively in enhancing the physical and the bio-chemical reactions by Edwards and Fletcher (1988). Thus, it explains that the higher temperature in summer enhances the life activity of the plant, microorganism and earthworm as well as the synergistic effect among them; this was the reason for the higher removal efficiency. It is worth noting that the process still performed well in the winter, this may be attributed to the living of the *Ophiopogon japonicus* and *Rhododendron simsii Planch* in the soil. Furthermore, the covering of the *Ophiopogon japonicus* above the tanks could offer a heat preservation function, which enabled the continuing biological activity inside the soil.

Conclusions

A set of gravity flow stepped eco-filter process was conducted to treat GW generated from a single farm house over an entire year, and the impacts of HLR and environment temperature were investigated in this experiment. The average values of the most indexes in the influent GW were

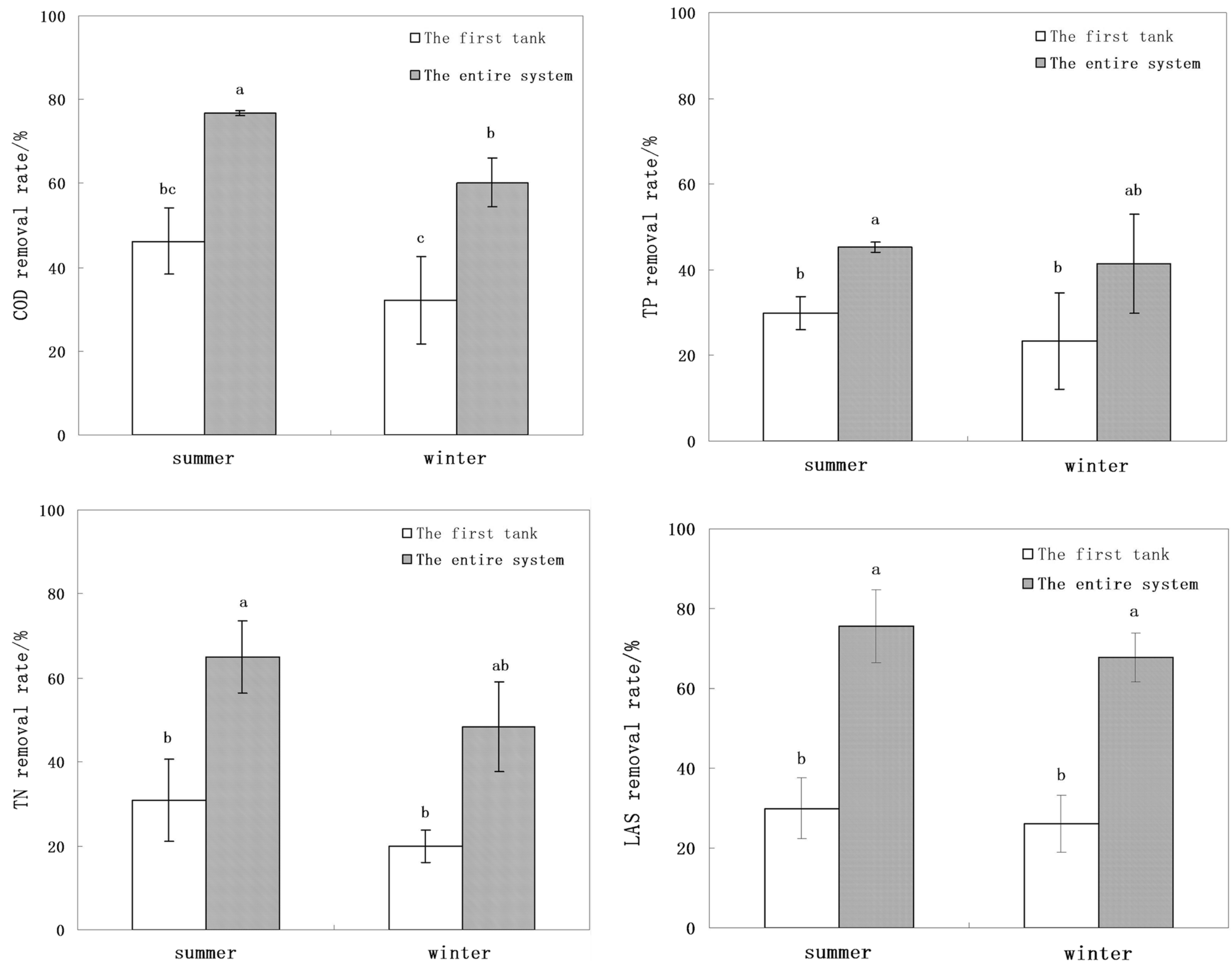

Fig. 4 Effect of seasonal temperature change on the removal rates of the process

relatively low but in the range of the previous study, except for that of the LAS. The removal rates changed differently with the increase of HLR, and the optimal HLR is in the range of 0.2–0.4 $m^3/(m^2$ day) for this facility. The facility was operating all year round; the average removal rate of the COD, TN, NH_4^+-N, TP, turbidity and LAS was 67, 55, 64, 43, 68 and 71%, respectively.

The average removal rates in summer were all higher than those in winter. However, the process still performed well in winter. The difference of the COD removal rate was significant ($p < 0.05$) between the summer and winter and, however, that of TP was hardly observed. Clogging has never occurred in the process while it was operating over one entire year. Overall, the facility demonstrated high performance, low cost and easy maintaining.

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